

# Experimental verification of resonance instability bands in quadrupole doublet focusing channels

K. Fukushima, K. Ito, H. Okamoto, S. Yamaguchi, K. Moriya, H. Higaki, T. Okano *Hiroshima University, Japan*  
S. M. Lund, *Lawrence Livermore National Laboratory*

## Introduction

Quadrupole doublets often employed for beam focusing in transport channels and linear accelerators including possible heavy ion fusion drivers and common drift tube linacs. Non-scaling fixed field alternating gradient rings are also composed from many doublet cells. This broad use indicates the practical importance of understanding the collective nature of high-quality hadron beams propagating in long, periodic doublet channels. We experimentally investigate the dynamical property of doublet focusing employing a compact linear Paul trap system developed at Hiroshima University. This trap system is called “S-POD (Simulator for Particle Orbit Dynamics)” and we exploit an approximate beam-frame equivalence between collective evolution of a charged particle beam in a transport lattice to that of a non-neutral plasma in a trap to inexpensively and efficiently explore long-path transport issues.

## About S-POD

(Simulator for Particle Orbit Dynamics)

### Transverse Hamiltonian :

$$H = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2} K(\tau)(x^2 - y^2) + \frac{q}{mc^2} \phi(x, y, \tau)$$

$\phi$  : scalar potential of Coulomb interactions  
 $K(\tau)$  : periodic focusing potential

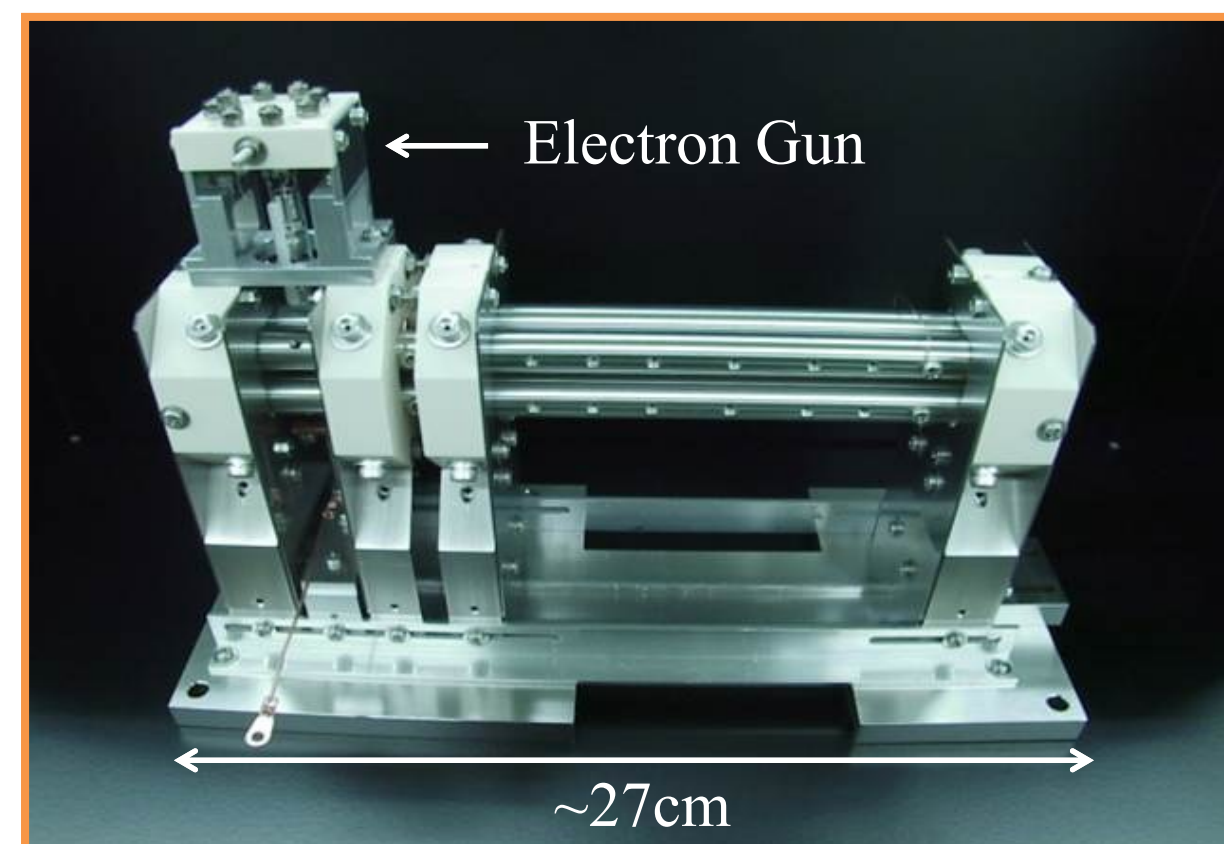
### Merits:

- Very compact and inexpensive
- Extremely wide parameter range
- Lattice controllability
- High resolution and accuracy measurements

### Measurement procedure

1. Ionize neutral Ar gas with a low-energy electron beam (Section A).
2. Confine Ar<sup>+</sup> ions typically for 1~10 msec corresponding to  $10^3 \sim 10^4$  FODO periods.
3. Switch off the potential wall of Faraday-cup side to dump ions for measurement.
4. Reconstruct the axial potential well with slightly varied amplitude for the primary focusing wave (i.e., the bare betatron tune  $\nu_0$ ).
5. Repeat procedure to scan tune-space.

### S-POD photograph



### Main Components

Linear Paul trap (multi-section)  
Ion detectors (Faraday cup)  
Vacuum system  
(achievable pressure  $< 10^{-8}$  Pa)

## Summary

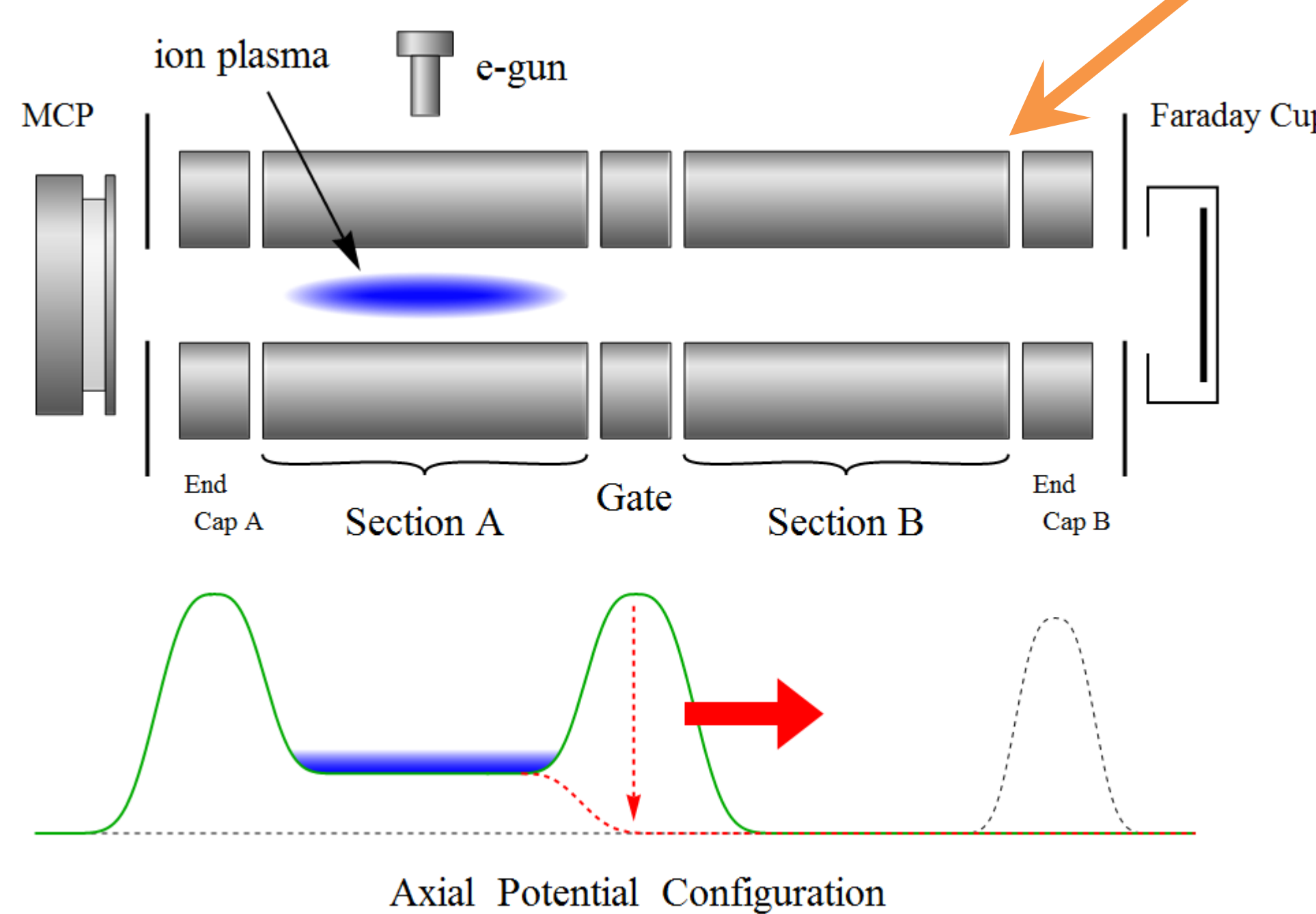
We carried out experiments and Warp simulations to study space-charge resonances of an intense charged-particle beam propagating in periodic quadrupole doublet focusing channels. A large number of heavy ions were stored in a compact linear Paul trap (S-POD) to reproduce the collective beam evolution over thousands of doublet cells.

- In the case of the horizontal and vertical net focusing effects were equal ( $\nu_x = \nu_y$ ), three noticeable stop bands appeared near the bare tunes  $\nu_0 = 1/6$ ,  $\nu_0 = 1/4$  and  $\nu_0 = 1/3$ .
- The observed stop-band distribution was not significantly influenced by the choice of higher-frequency Fourier harmonics in the plasma confinement field but slightly shifted depending on the plasma intensity.

We can conclude that the ideal doublet focusing is dynamically very similar to the simple sinusoidal focusing, regardless of the filling factor  $\xi$  and drift ratio  $\zeta$  over the broad range explored. At least, the locations of major stop bands observed are quite insensitive to the details of the doublet structure.

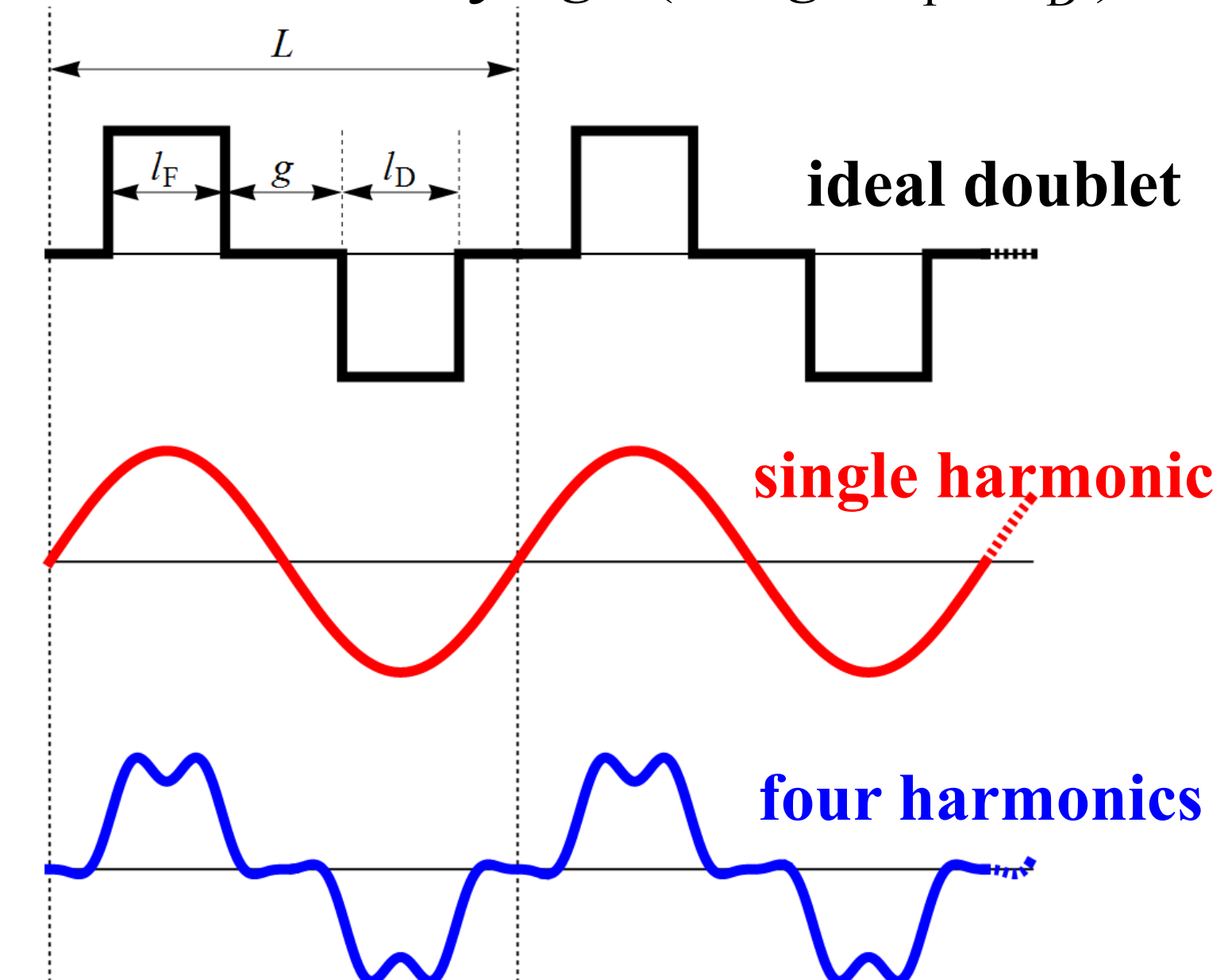
We also confirmed that each of the three stop bands splits into two parts when the transverse tunes are different ( $\nu_x \neq \nu_y$ ).

### Side View and Experimental System



### Focusing System (apply to all rods)

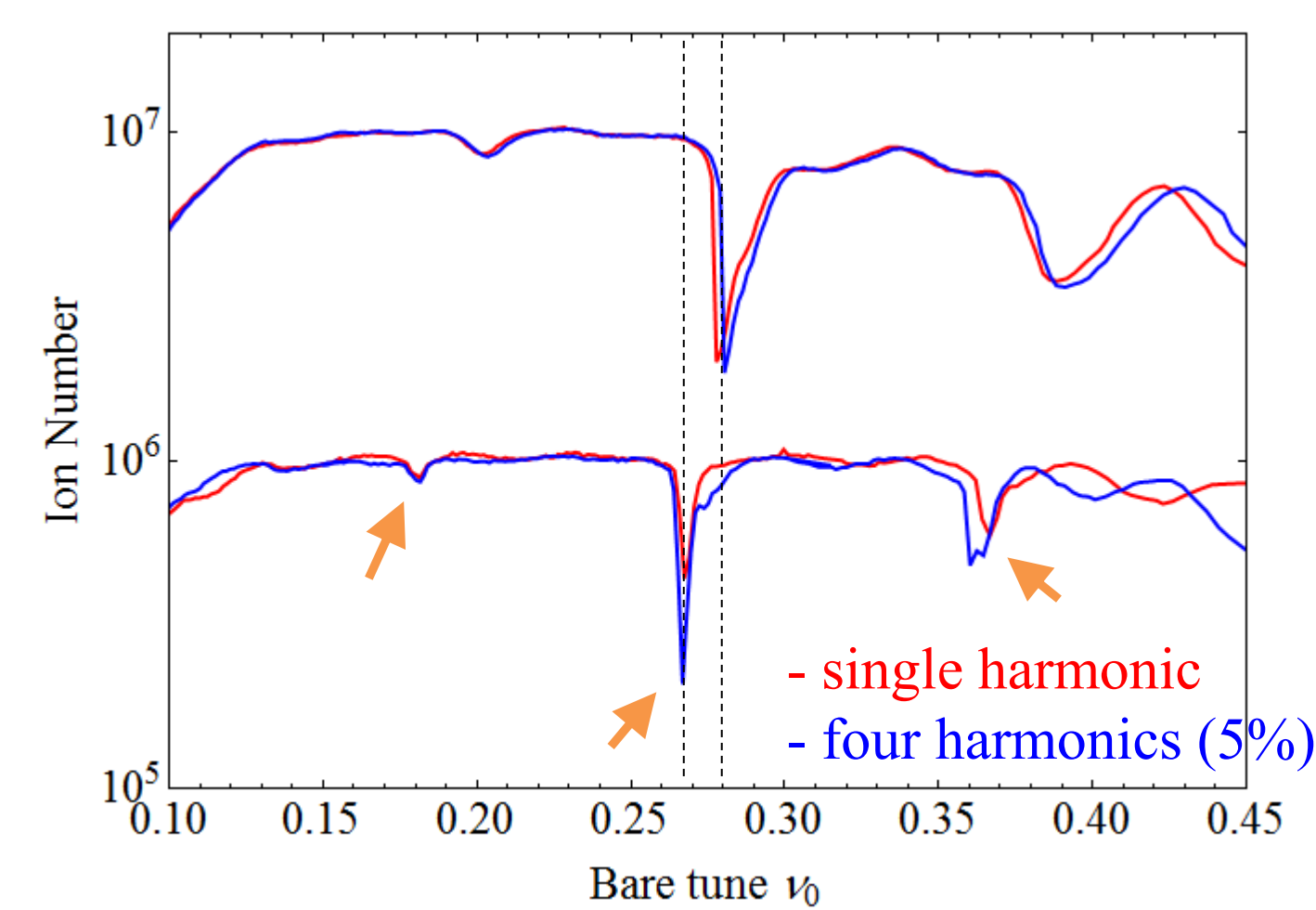
Filling Factor :  $\xi = (l_F + l_D) / L$   
Drift Ratio :  $\zeta = g / (L - g - l_F - l_D)$



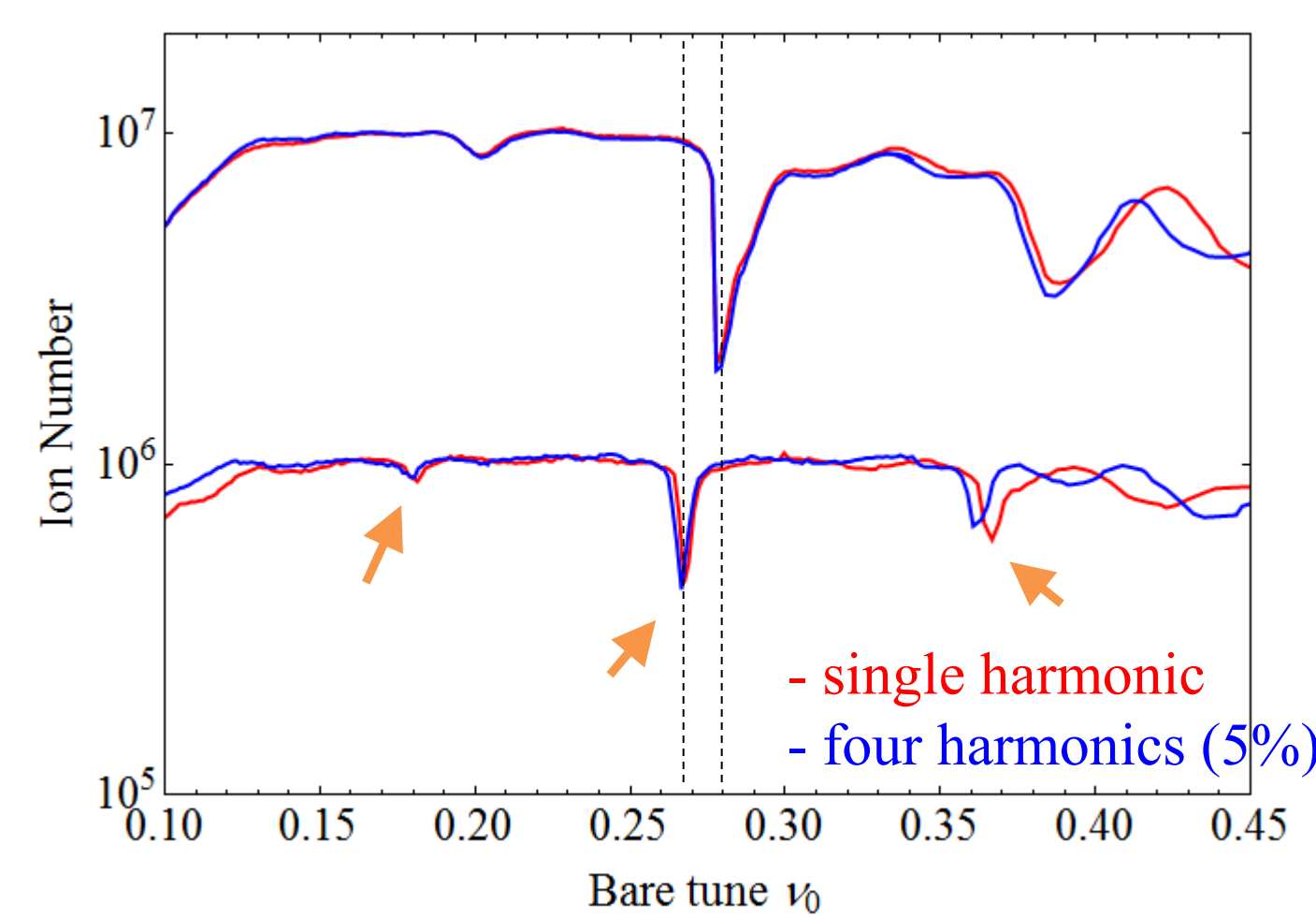
## Results

### Case A : $\xi = 0.5$ , $\zeta = 1.0$

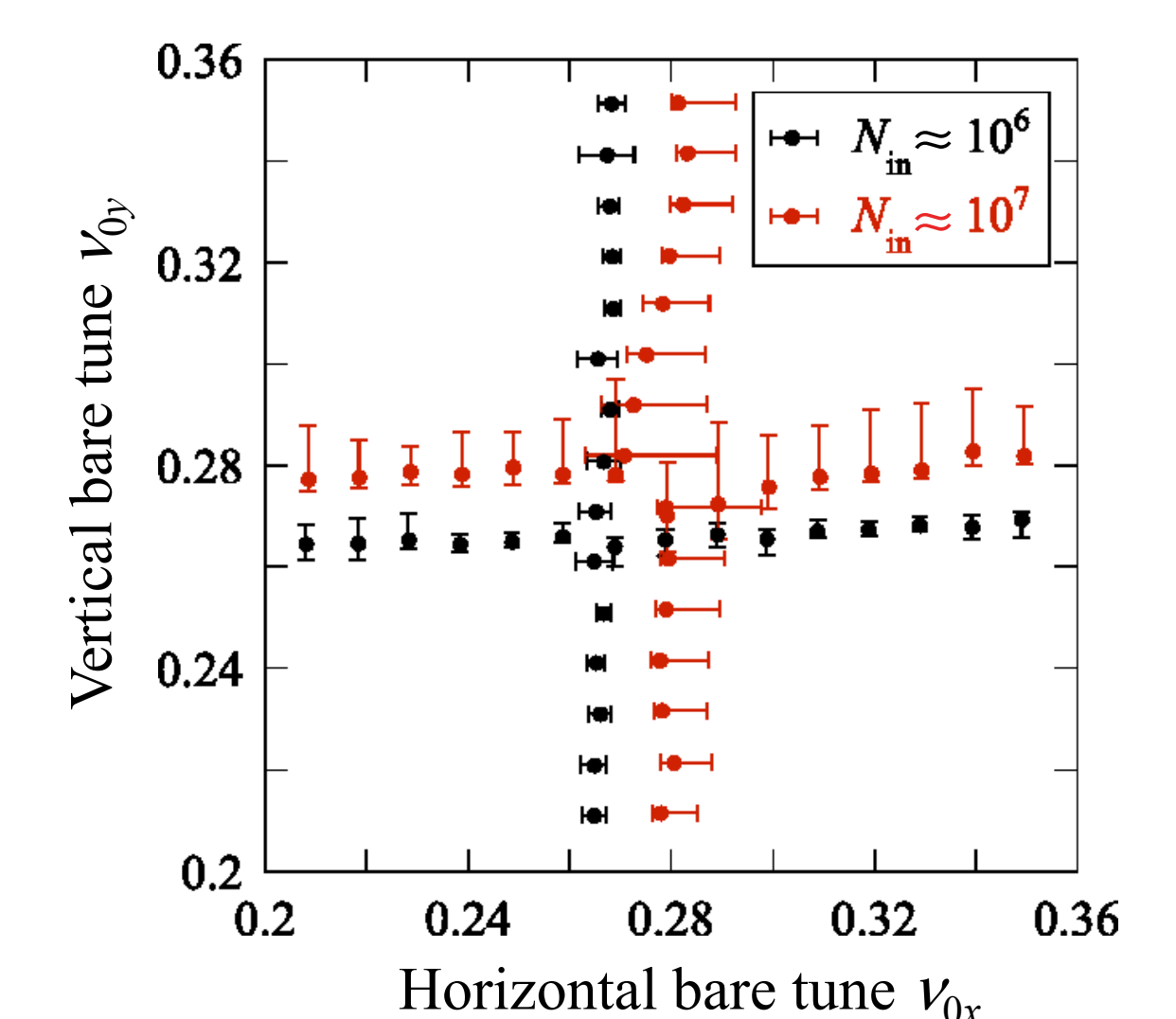
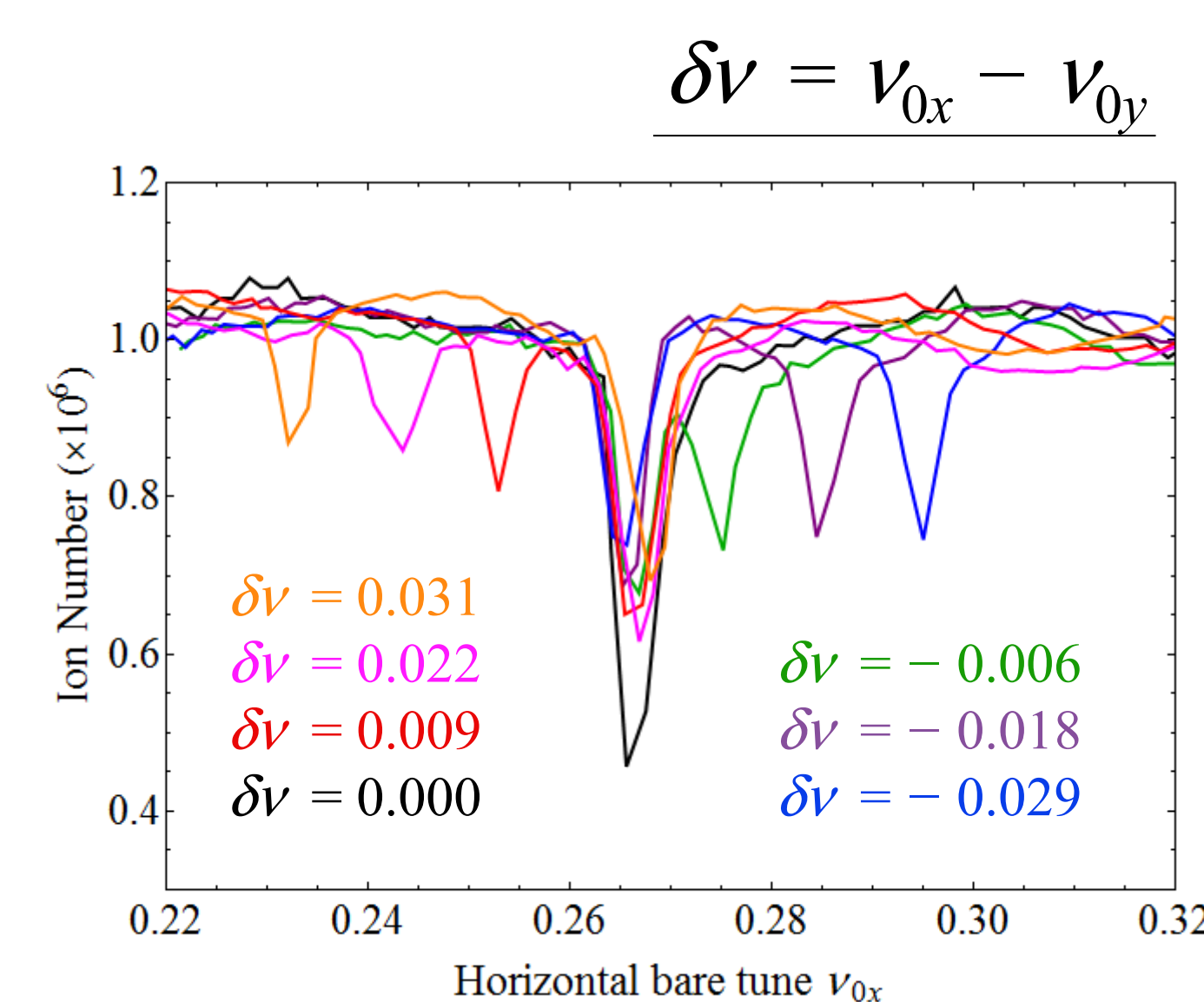
#### S-POD Experimental Results



### Case B: $\xi = 0.25$ , $\zeta = 0.1$

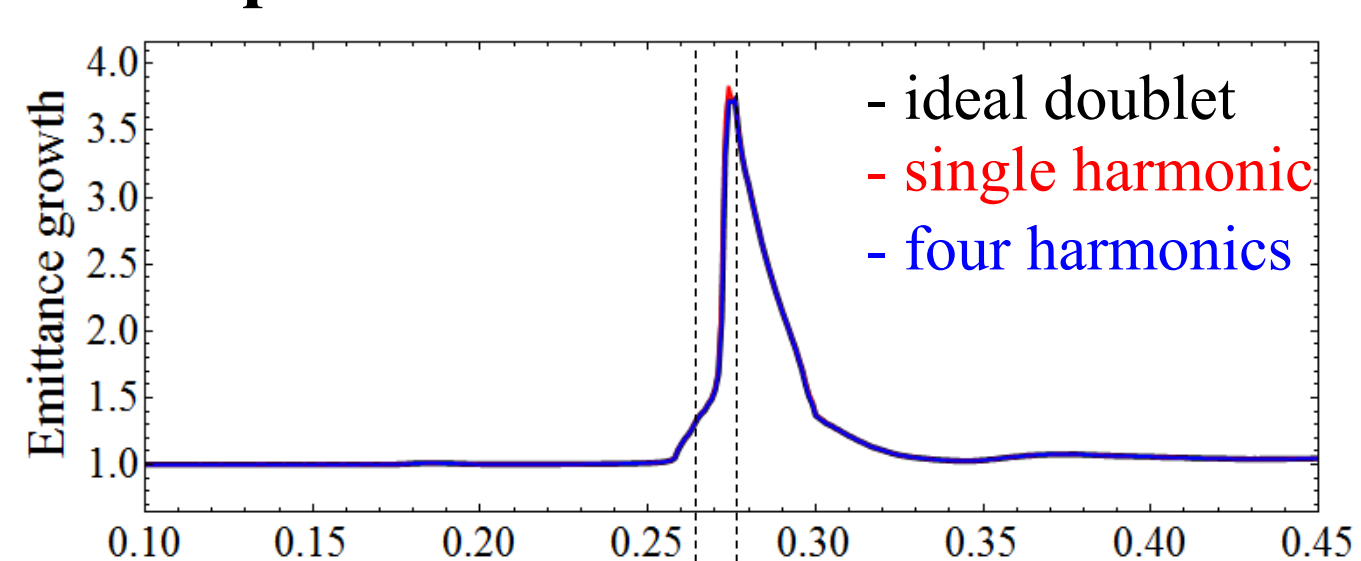


### Different tune case (single harmonic)

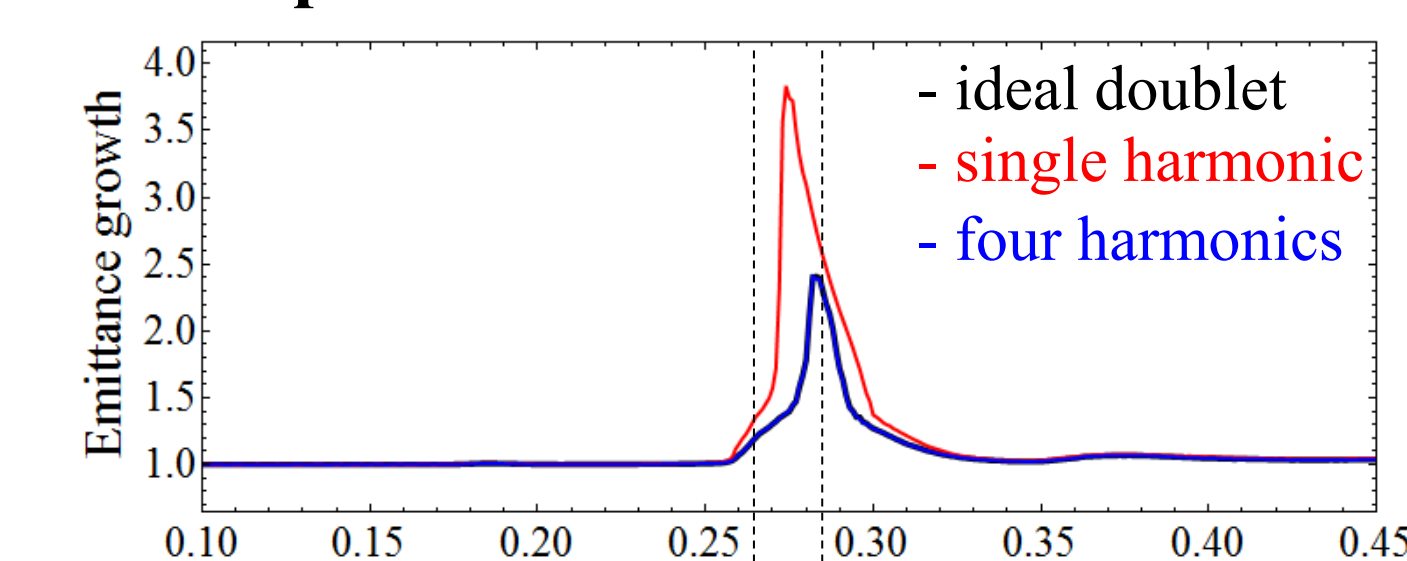


### 2D-WARP Simulation Results (Thermal equilibrium distribution, After 100 periods)

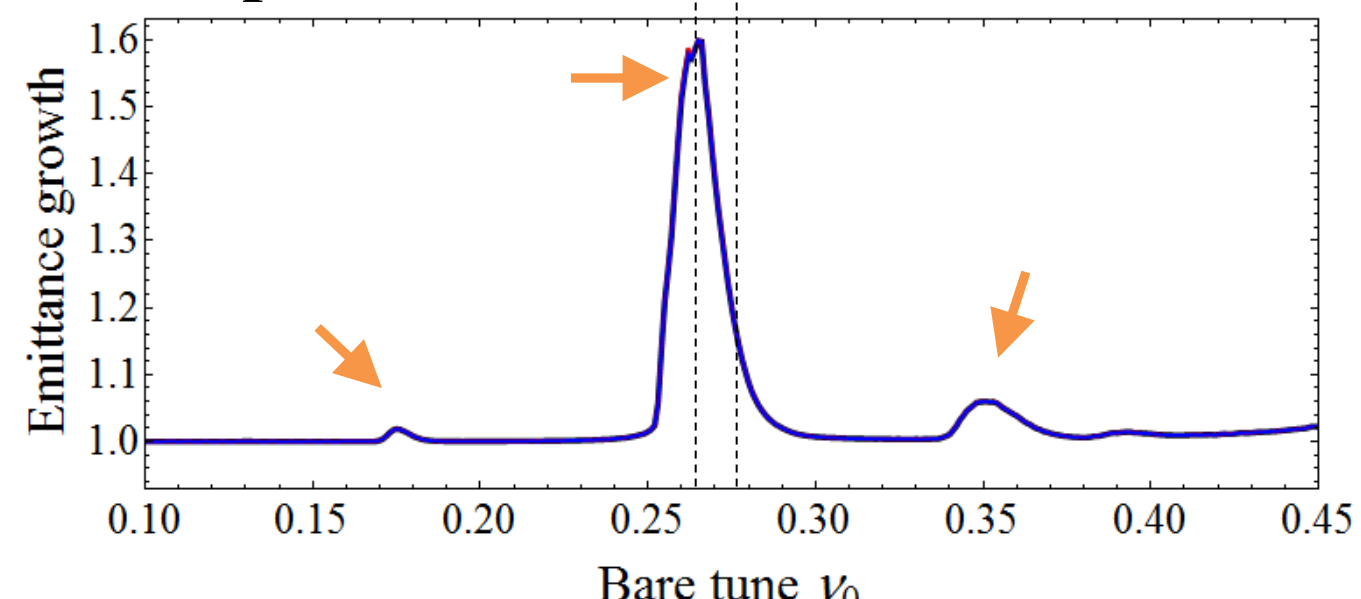
#### Tune depression : 0.80



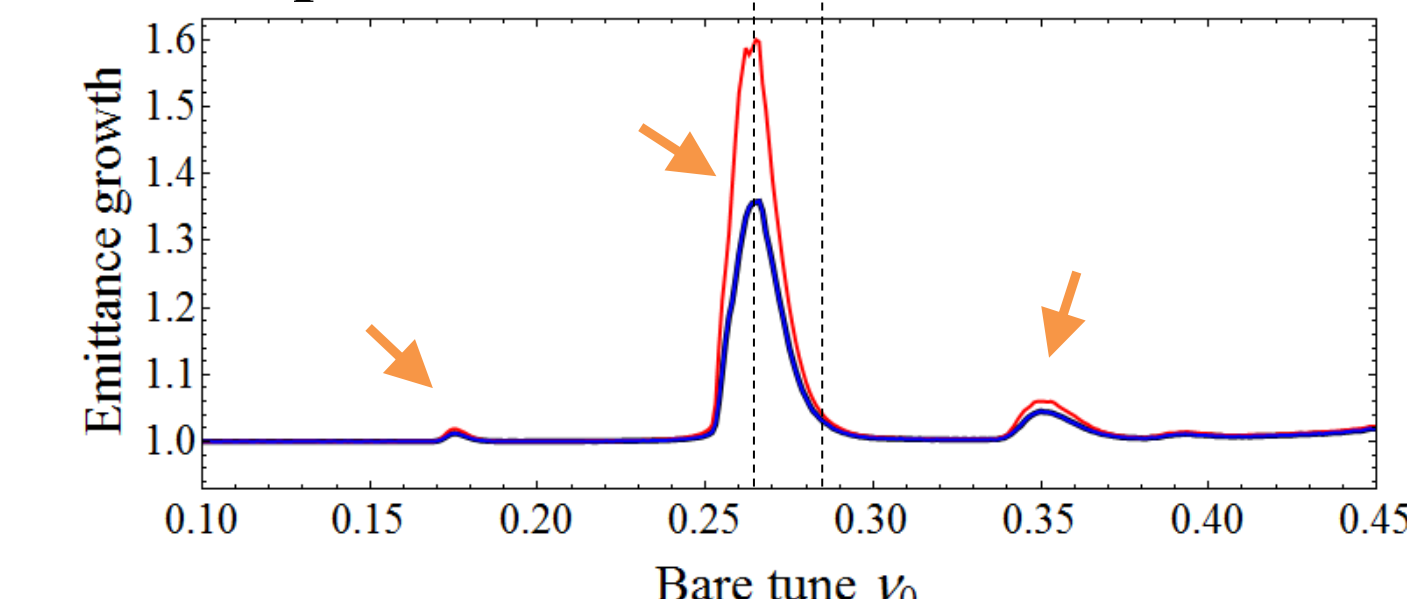
#### Tune depression : 0.80



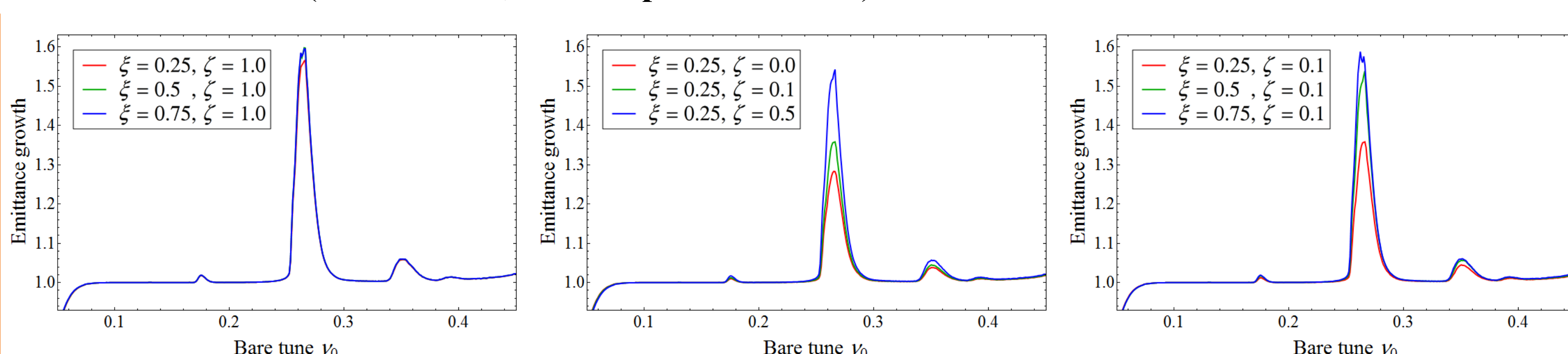
#### Tune depression : 0.90



#### Tune depression : 0.90



### Various Simulations (ideal doublet, Tune depression : 0.90)



#### Tune depression : 0.90

